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Evaluation of the Physiological Parameters Associated with the Propellant Handler's Ensemble

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ABSTRACT: Work involved during the preflight preparation of spacecraft involves the handling of materials that are very toxic to humans. These toxins attack the respiratory and skin systems and, therefore, impose the requirement for full suit enclosures. The weight, structure, and operating parameters of such a suit can be expected to have a significant effect upon the metabolic and thermal responses of the user, especially in high workload situations and ambient temperature extremes.

This paper describes the testing of the operational version of the Propellant Handler's Ensemble (PHE). In particular, parameters affecting the physiology of the user were measured during a work-rest regimen performed in three temperature environments: −7, 23, and 43°C (20, 74, and 110°F). Six subjects performed tests in these environments in two versions of the PHE, the autonomous backpack version and the hoseline supplied configuration. Measurements included heart rate, four skin temperatures, rectal temperature, oxygen and carbon dioxide in the helmet area, suit pressure, and interior suit temperature.

It was concluded that the weight and configuration of the suit significantly influenced the physiological stress on the user. The weight, at 29.5 kg (65 lb) for the PHE and backpack, proved to be a primary stressor, as indicated by elevated heart rates. The high workload portion of the protocol also taxed the limit of the environmental control unit because of the increased respiratory requirements. Oxygen levels dropped as much as 4% below resting levels and the carbon dioxide level increased by a similar amount. Finally, thermal stress is clearly evident, especially in the 43°C (110°F) tests.

State-of-the-art design techniques in whole body suits do not provide solutions to these problems. Therefore, it has been necessary to institute operational restrictions and impose medical and physical standards to avoid situations that could adversely affect the well-being of the worker.

KEY WORDS: protective clothing, physiology, totally encapsulating suits, thermal stress, propellant handling

The Kennedy Space Center is the focal point for the preflight checkout and launch of many of this nation's spacecraft. Propulsion systems on these spacecraft rely on a variety of propellants, many of which are extremely toxic to humans. Examples of these toxins are nitrogen tetroxide, hydrazine, and monomethyl hydrazine, all of which have threshold limit values of less than 3 ppm. Despite considerable efforts to institute engineering controls, the potential exists for exposure to workmen during operations such as propellant transfer. Since

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these toxins are damaging to both the skin and respiratory systems, a whole body protec suit must be employed to provide proper protection.

The use of whole body suits can introduce a variety of problems, not the least of w is its effect on the physiology of the user. The weight and encumbrance of the suit contrib an extra workload above the assigned productive work. Thermal loads are imposed restrictions to vision, mobility, and dexterity are experienced. The cumulative effects c these factors may prevent the workman from actually working productively, and they also affect his safety.

As reported earlier (in this publication), the Kennedy Space Center recently embar on a program to replace the original whole body protective suits called the Self-Conta Atmospheric Protective Ensemble (SCAPE). The SCAPE was tested extensively in laboratory. The new suit, called the Propellant Handler's Ensemble (PHE), was m available to this laboratory after development of the prototype. Testing of this proto provided additional data that was fed into the final design of the suit. Many human fa considerations were noted resulting in some rather substantial changes. For example, emergency air system had to be deleted from the design because it added nearly 9 kg to overall suit weight of 39.5 kg (87 lb). This burden proved to be too much, especially the small user.

It is the purpose of this paper to communicate the data resulting from an extensive se of physiological tests on the final production version of the suit hereafter called the qu fication (qual) suit.

Methods

The intent in testing the PHE was to examine the factors affecting the physiology of user during worst-case workloads and extremes of temperature. Therefore, a protocol developed involving a work-rest regimen that would take place in an environmental chaml

Initial testing was carried out in normal laboratory conditions to provide a baseline aga which data from the cold and hot temperature extremes could be compared.

A bit of background information is necessary to understand the rationale for selectio the test protocol. Experience gained in the field shows that in normal operation, the wor walks several hundred meters to his worksite, sometimes having to climb several flight stairs. He then performs light plumbing repairs or he adjusts or monitors valve or p panels. He then walks back after a 2-h work period. Worst-case workload would invo the rescue of a fallen co-worker during a hazardous operation. This would likely be sh duration, intensive work.

Laboratory experimentation has shown that even the better conditioned test subj (VO_2 = 50 mL/kg/min) could not perform treadmill Bruce Stage III while wearing the s In the laboratory, the Bruce treadmill protocol has served as a reference for the testing a wide variety of protective equipment. It also is used as the basic qualification protocol new subjects and therefore, has, been established as a baseline physiologic load.

A basic description of the suit is necessary to understand other aspects of the proto origin. The PHE is a completely enclosed whole body suit made of chlorobutyl coa Nomex material. This is one of very few materials that is relatively impervious to propellants, yet can be joined together into leak-proof seams, and can withstand the rig of repeated flexing. The suit has two methods of environmental control. One version called the backpack suit. It contains an Environmental Control Unit (ECU) that is w on the user's back and is powered by liquid air. The ECU provides gaseous air after expans through a heat exchanger. The user's body heat contributes to the heat transformation. T primary air is introduced into the ECU's venturi at a rate of approximately 42.5 L/min (

TABLE 1—*Testing procedure.*

Time, min	Activity
−10	Sensor subject, perform final calibrations
0	Start test, collect baseline unsuited data (heart rate, temperatures)
10	Start suiting
20	Suiting complete, enter chamber or laboratory
40	Exercise 3 min on treadmill, 1.7 mph/10% grade
43	End exercise, start recovery period
63	Exercise 6 min: 3 min at 1.7 mph/10% grade and 3 min at 2.5 mph/12% grade
69	End exercise, start recovery period
89	End of test

standard cubic feet/minute (SCFM)). Total flow can reach 425 L/min (15 SCFM), and this flow is divided in an air distribution manifold to allow approximately 60% distribution to the helmet area with the remainder being circulated to the arms and legs. No face mask is worn. This air also provides much needed cooling in the normally experienced hot temperature environments. This version of the suit allows the user to be completely mobile, although the weight penalty, at 29.5 kg (65 lb), is heavy.

The other version of the PHE is the hoseline suit. This suit relies on a hoseline to supply air for respiratory and cooling purposes. A Vortex cooling unit is used. The internal air distribution is identical to the backpack version with the exception that air is not recirculated. Normal flows are about 170 L/min (6 SCFM). This suit has the advantage of relieving the user from carrying the 17.7-kg (39-lb) backpack, but does encumber him with a tether, that is, hoseline.

Considering the foregoing, a protocol was developed and is shown in Table 1.

The first 20 min of suited testing (20 to 40) allowed for the collection of baseline conditions in the suit while the subject stood unsupported. The first exercise period then provided a physical stress for the subject and the suit's ECU. Recovery from this was monitored during the second 20-min standing rest period. If this were satisfactory, that is, the ECU caused the helmet monitored level of oxygen to return to before-work levels, the second and more difficult exercise was imposed. A final 20-min recovery period was then allowed.

This protocol was carried out in three environmental conditions: cold chamber at −7°C (20°F), laboratory at 23°C (74°F), and hot chamber at 43°C (110°F). These extremes were chosen because of the possibility of experiencing the cold during night deservicing in the desert at Edwards Air Force Base and day servicing at the Kennedy Space Center in the summer. Each test was carried out at least four times. The actual test program is shown in Table 2.

In the normal test scenario, the volunteer subject was instrumented for a single channel of electrocardiogram (ECG) using a Hewlett Packard telemetry system. This ECG was received and displayed on a memory scope, fed to a heart-rate counter, and finally recorded on both strip chart and magnetic tape recorders.

TABLE 2—*Actual test program.*

Type	Cold	Laboratory	Hot
Backpack PHE	6	6	6
Hoseline PHE	4	5	7

The subject was also sensored for four skin temperatures and rectal temperature usin YSI Series 700 thermistor probes. Skin sites were the forehead, the upper arm, the lef chest area, and the right thigh. The suit interior temperature was monitored in the helme and torso areas. All probes were connected to a Digitec Model 2000 datalogger.

A gas sample line was inserted into the helmet area, just in front of the nose, to monito the oxygen and carbon dioxide concentrations throughout the test. This line was connecte to a Beckman Metabolic Measurement cart that provided continuous analog output to strip chart recorder and also printed 1-min average value data on a computer.

Suit pressure was monitored using a National Semiconductor integrated pressure chip connected to a locally produced buffer amplifier. Output was recorded on the strip chart.

Finally, the subject was equipped with a Snoopy hat type communications carrier. This afforded communications to the test conductor, safety monitor, and technician via an operational intercommunication system. All voice communication was recorded.

In the laboratory, a Quinton 18-60 treadmill and automatic programmer were used. Inside the Blickman environmental chamber, a Quinton Q-55 treadmill allowed the necessary head clearance and provided the selected workloads.

Results

The subjects used in this test series were all volunteers. Two females participated in some of the tests and four males completed all six configurations. The duration of the test series precluded participation by all subjects throughout the many months of testing. A total of eight subjects ranged in age from 26 to 49 years (mean = 36) and ranged in height from 157 to 193 cm (mean = 178 cm). Weight ranged from 62.1 to 95.2 kg (mean = 80.1 kg). Oxygen uptake, as measured in a standard stress test, with the Bruce protocol ranged from 36.2 to 54.8 mL/kg/min (mean = 42.5 mL/kg/min).

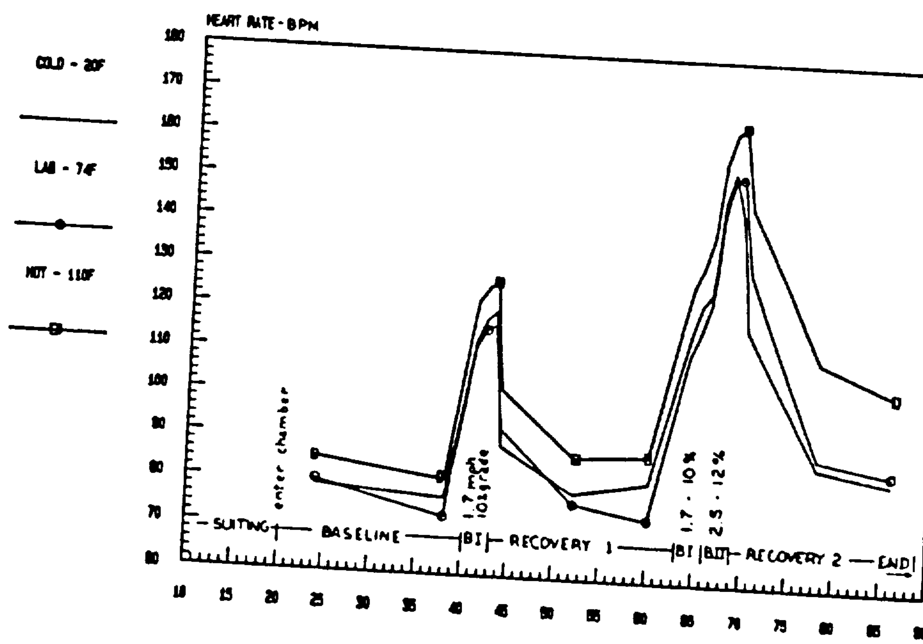

FIG. 1—*Heart rate for the backpack version (average of six subjects).*

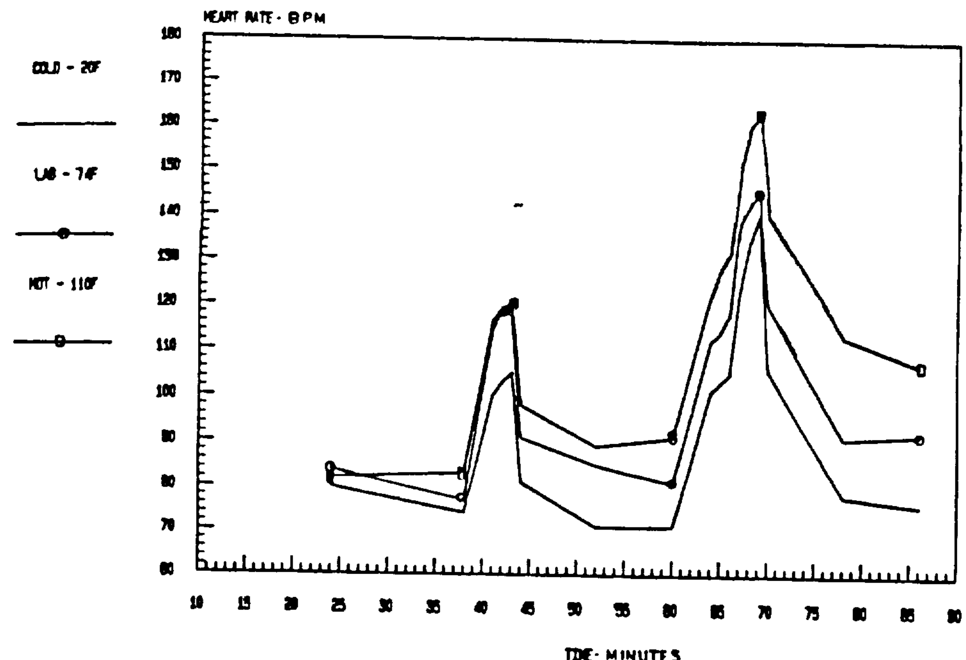

FIG. 2—*Heart rate for the hoseline tests (average of two, five, and seven subjects).*

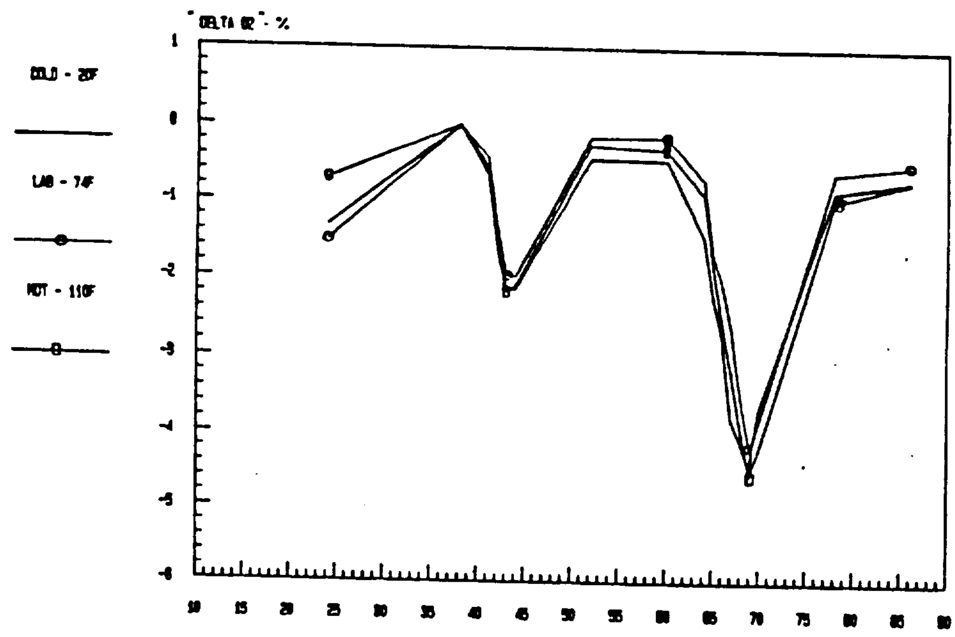

FIG. 3—*Delta oxygen concentration for the backpack suit (average of six subjects).*

The data taken were extensive but will be summarized here on a series of figures. Heart rate and average (over 1 min) oxygen and carbon dioxide concentrations were gathered continuously but are plotted at only the most meaningful times. Temperature was recorded every 2 min, but it also was plotted at only the most important times.

The heart rate responded as expected to the imposition of the load and temperature. Figure 1 shows heart rate in beats per minute (bpm) for the backpack version of the suit during all three temperature environments. Notice the rapid increase in heart rate to the first exercise bout at Minute 40. After only 3 min of slow walking, the average rate reached 127 bpm in the hot test. The rate does not recover to the resting value despite 20 min rest. The second exercise period drives the heart rate to 165 bpm. This exercise is very difficult, especially in the heat. One large contributor to the work is the difficulty in actually moving the legs fast enough to keep up with the treadmill at 2.5 mph. One actually pumps air from the leg on each step, a fact that is readily apparent in the suit pressure tracing. Heart rates in the cold and laboratory tests are slightly lower, but still show the difficulty of performing work that would be considered easy without the suit.

The data from the hoseline tests are shown on Fig. 2. Once again, the response to work is apparent although less than that of the backpack suit. The decreased response in this configuration is due to the decreased weight of the suit (11.8 versus 29.5 kg) and the superior gaseous environment of this suit as will be shown soon. Large differences in the heart rate can be noted between the different temperature tests. Since actual physical work is the same in each test, the higher response of the hot test during the second exercise is probably due to heat buildup in the suit.

The next two graphs, Figs. 3 and 4 plot oxygen concentration. This is actually specified as delta oxygen because of the fact that initial oxygen concentration after every backpack

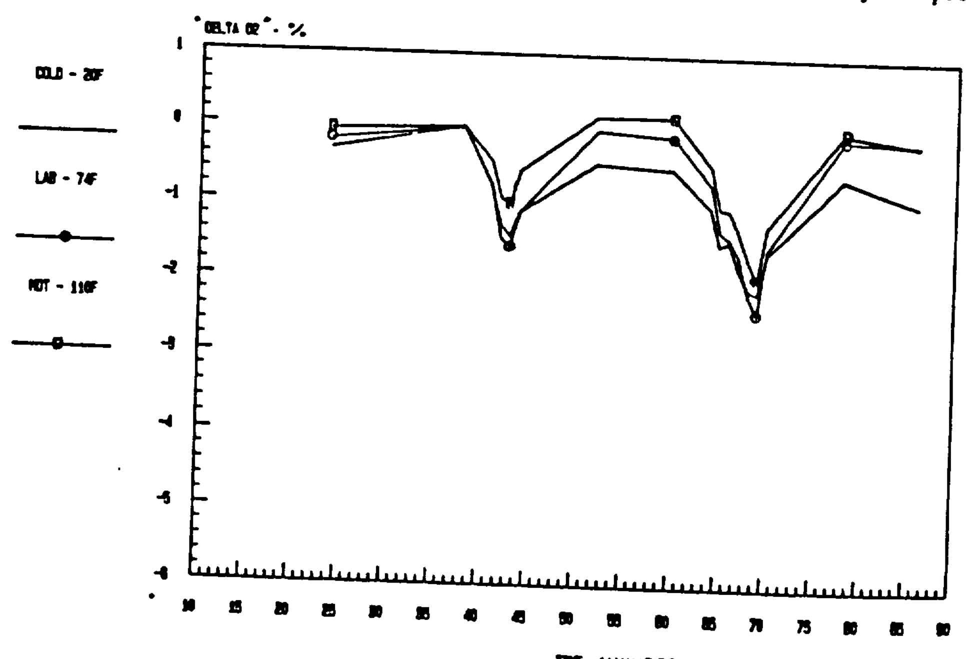

FIG. 4—*Delta oxygen concentration for the hoseline suit (average of four, five and seven subjects).*

fill is slightly different. Liquid air at the Space Center is manufactured from liquid nitro and oxygen. The air becomes oxygen rich after a period of weeks because of nitrogen boil Therefore, a baseline concentration is selected after the first 20 min of baseline acquisiti or Minute 38. All other oxygen concentrations are then expressed as a difference from value. Figure 3 shows the response of the backpack suit to all three environments. The d O_2 decreases to −2.18% after the first exercise and drops further to −4.56% after second exercise. This is, of course, a concern when one considers the Occupational Saf and Health Administration (OSHA) limit of 19.5% minimum oxygen. This was not a probl in most of these tests as the absolute value at Minute 38 was 24% or greater. On the ot hand, low initial concentrations, due to poor mixing or the use of liquified atmospheric would most likely result in hypoxic exposure.

The hoseline delta oxygen data are plotted on Fig. 4. Note the general lessened respon Minimum delta oxygen during the first exercise was −1.57% and −2.41% during the sec exercise. It was noted that several of the subjects considered the laboratory temperat test to be the most difficult of the three, but no immediate explanation can be found.

The next parameter of interest was the carbon dioxide concentration in the helmet ar Figure 5 shows the backpack suit results. The significant point of this data is that carl dioxide is always greater than 0.67%, even during rest. Note that the threshold limit va (TLV) for an 8-h working day is 0.5%. However, these suits are infrequently worn m than 2 h, and the maximum duration of the backpack is just about 3 h. The short-te exposure level (STEL), as specified by the American Conference of Governmental Industi Hygienists (ACGIH) is 1.5%. This value is exceeded during both of the exercise perio Note the maximum during the second exercise of 3.97%. Data plotted in the Bioastronaut Data Book show that carbon dioxide at twice this concentration produces no detecta effects until the 10 to 15 min exposure is reached. One may suggest that the 1.5% ST

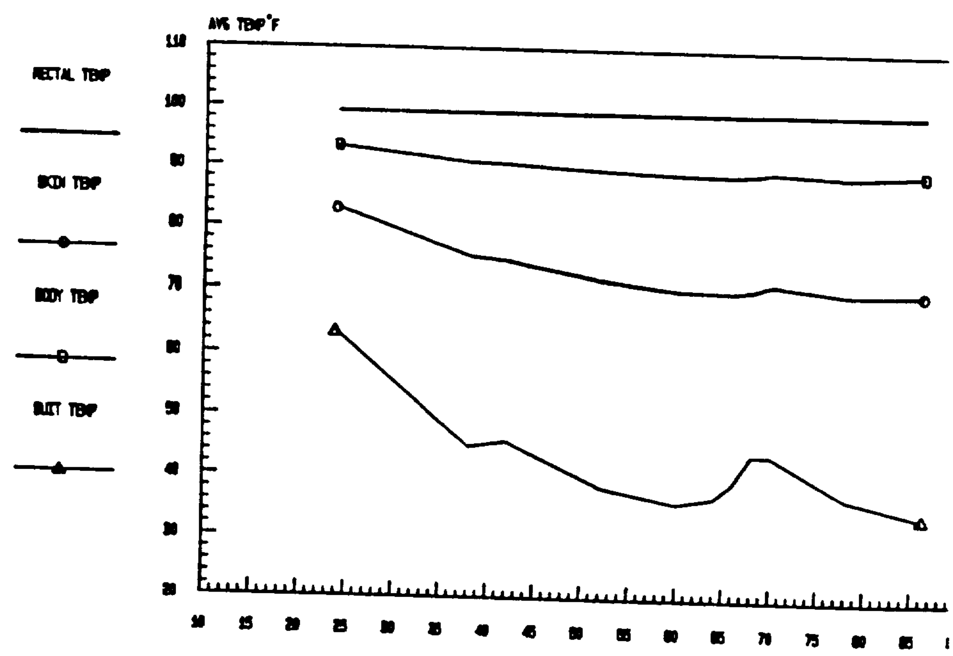

FIG. 7—*Temperature profiles for cold backpack tests at 7°C (20°F) (average of six).*

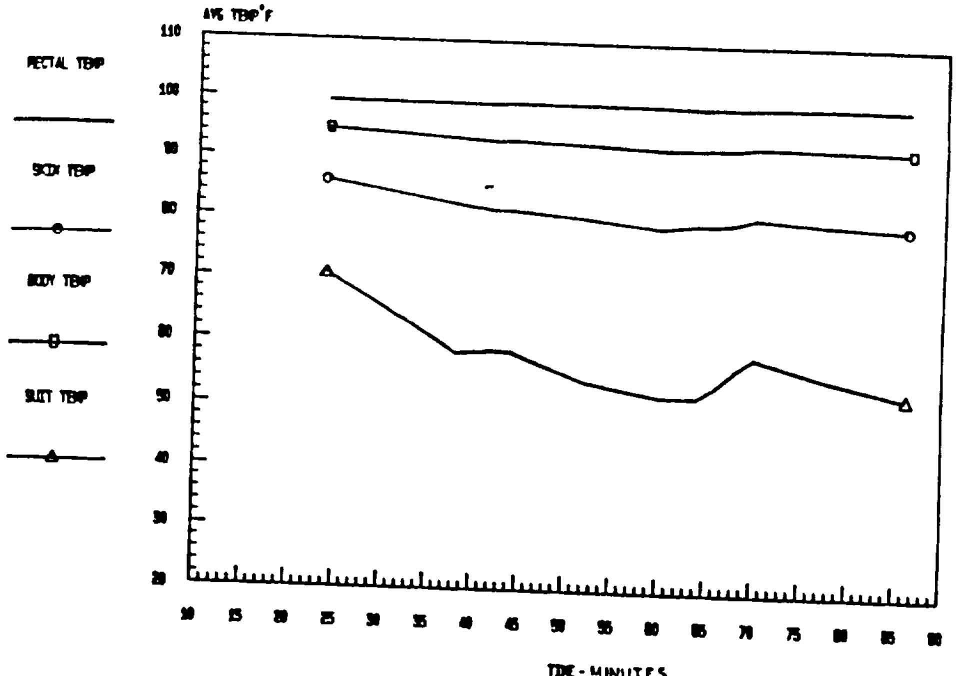

FIG. 8—*Backpack suit test at laboratory temperatures of 23°C (74°F) (average of six).*

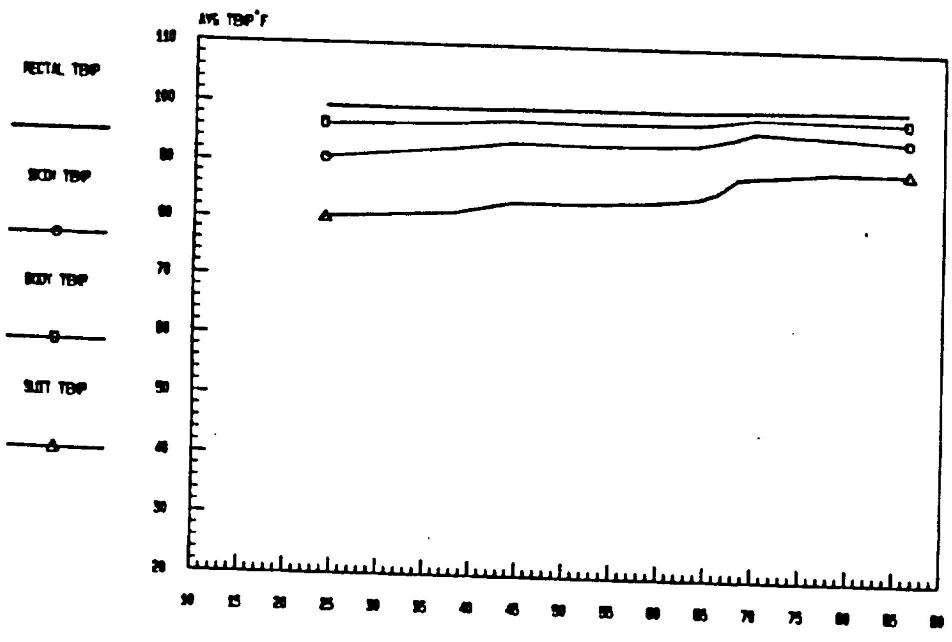

FIG. 9—*Temperature profiles for hot backpack tests at 43°C (110°F) (average of six).*

may not be realistic. Little evidence of adverse reaction to carbon dioxide could be noted in these tests, in spite of an alert posture to a possible response. Inspiration of air containing greater than 2% carbon dioxide is known to trigger significant increases in minute volume. While this was not monitored, particular attention was directed toward detection of other symptoms such as discomfort, fatigue, dizziness, headache, and shortness of breath.

The hoseline suit carbon dioxide data are found in Fig. 6. Once again, the gas concentrations are better. The maximum is 2.62% during the second exercise and was found during the laboratory test. The superior oxygen and carbon dioxide responses of the hoseline suit are due to the introduction of 6 SCFM of new air. Even though the vortex was fed 12 SCFM of new air, full opening of the control valve causes actual flow into the suit to be only 6 SCFM. The vortex was not operating during the cold tests and, as a matter of interest, is seldom used by field forces on hot days as they prefer to have the larger volume of ambient air rather than half that quantity of vortex conditioned air. This may lend some credibility to the thought that the cooling due to evaporation is more effective than cooling due to the lower temperature air being introduced into the suit.

The temperature profiles are now described over a series of six graphs (Figs. 7 to 12). Each of the test blocks has its own graph to avoid confusion of the four temperature profiles of interest. These profiles show suit, body, skin, and rectal temperature. The suit temperature is the average of the readings from the helmet and torso sensors. The sensors were located to avoid contact with the inside surface of the suit and the subject. The skin temperature was the average of four skin sensors located on the forehead, arm, chest, and thigh. The body temperature represented 0.65 times the rectal temperature plus 0.35 times the skin temperature.

Figure 7 shows a plot of these four temperature profiles during the cold backpack tests.

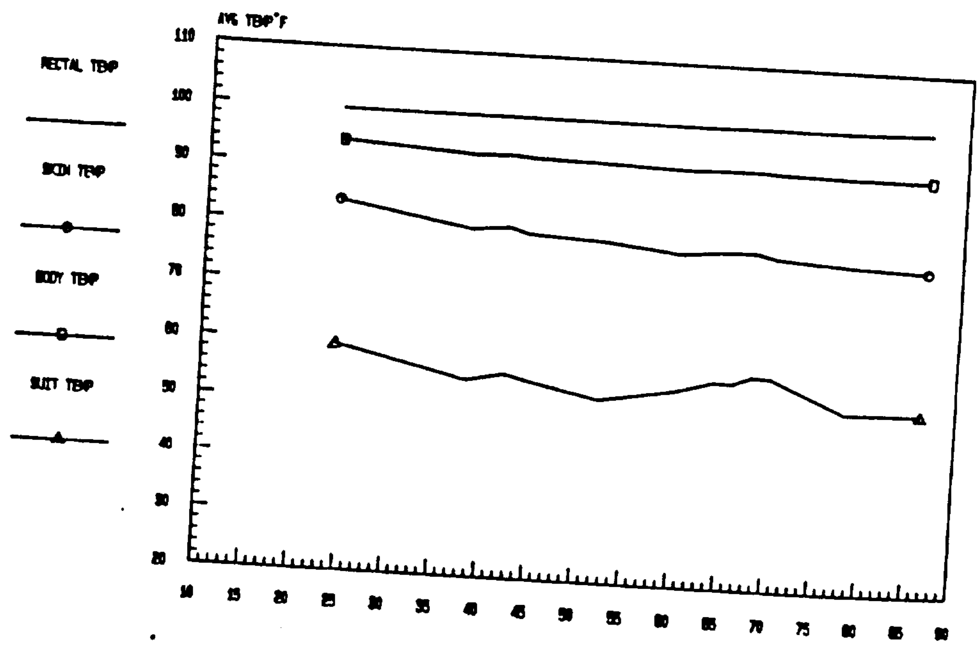

FIG. 10—*Cold hoseline suit temperature test at 7°C (20°F) (average of four).*

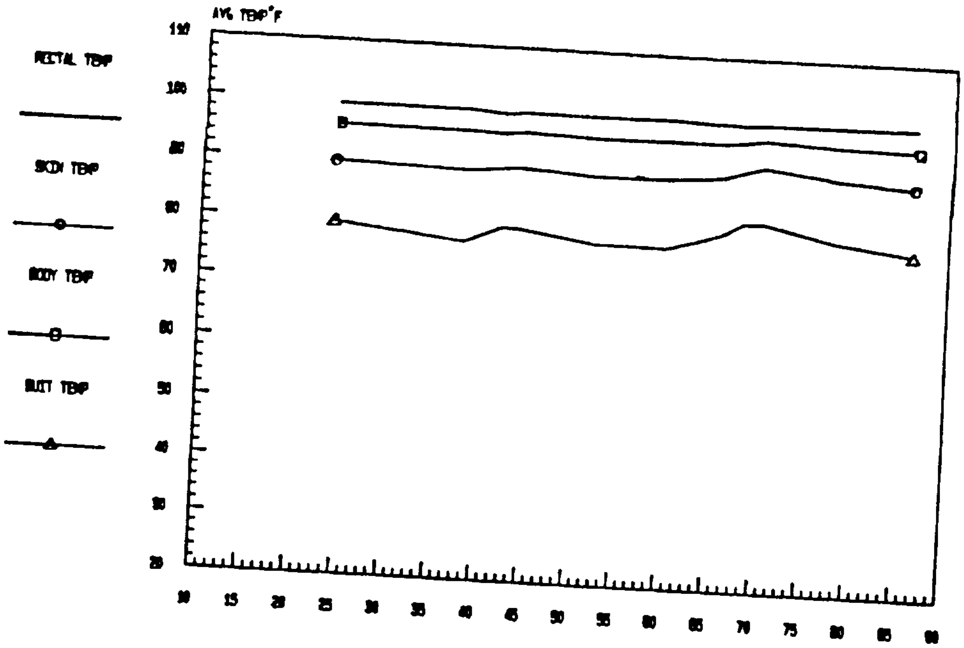

FIG. 11—*Hoseline suit test at laboratory temperatures of 23°C (74°F) (average of five).*

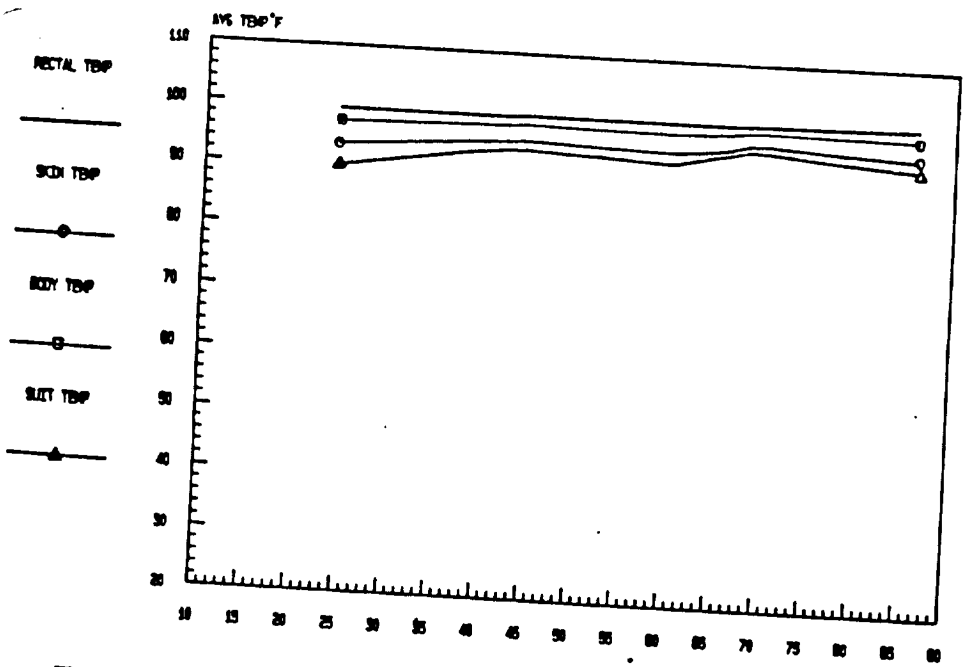

FIG. 12—*Temperature profiles for hot hoseline tests at 43°C (110°F) (average of seven).*

Temperatures are very cold and the subjects were uncomfortable, but none reached t point of uncontrollable shivering by Minute 89. Considering that the suit temperature dipp to 1.4°C (34.5°F) and the normal undergarment for the suit is a single layer of therm underwear, one can readily understand the problem. If one adds more insulation or clothi to the subject, then less heat is available to the ECU heat exchanger and the air suppli into the venturi becomes colder.

Figure 8 plots the backpack test at laboratory temperatures. One can observe that son cooling capacity is still available as the suit and skin temperatures show a steady decreas except for the exercise periods.

The backpack suit in the hot environment shown on Fig. 9 can not quite meet the coolir requirements in the hot chamber. A steady rise is apparent throughout.

Comparison of the hoseline suit temperature data in the cold, Fig. 10, with the backpac test shows that the effect of circulating 6 SCFM of ambient air into the suit is not as sever as the cryogenically supplied air of the backpack suit.

Figure 11 shows that the hoseline suit temperatures are basically stable. Figure 12 show the response to the hot environment. This is subjectively the hottest test. The suit, body and skin temperatures approach rectal temperature. Little gradient is visible therefore elim inating any real potential for relief on the part of the subject, even during the rest phase of the protocol.

Conclusion

Examination of these data make it clear that the imposition of a whole body suit, such as the PHE, can result in significant physiologic work on the user due to the protective system alone. Heart rates are driven to moderately high levels, supplied respiratory gases are not optimum, and thermal adversities are introduced.

The backpack version of the suit has the important advantage of allowing the user complete freedom to move about without a tether. The ECU provides superior cooling in the normal laboratory and hot environments. It provides nearly complete protection for time periods approaching 3 h. However, it burdens the user with a weight load that may be prohibitive to the small worker.

The hoseline suit offers reasonable conditions in the cold and lower ambient temperatures and provides superior oxygen and carbon dioxide characteristics. The 11.8 kg of suit weight is distributed about the body and mobility is good. The disadvantages are that the worker is tethered to a hoseline and the air supply must be large and of Grade D or better as both respiratory and cooling purposes must be satisfied.

This experience has made it clear to us at the Kennedy Space Center that the purchase and initial introduction of a new suit, even though it was of familiar configuration, is not a simple matter. Should an organization find itself in a position to institute personnel protection in the form of a full body suit, careful consideration must be made of all requirements. Suits that are currently on the market are not universally applicable. It is also impossible for the manufacturer to foresee particular needs and design appropriately.

Perhaps a more fundamental problem is the lack of universal suit testing methods. Suits do not (currently) fall under National Institute for Occupational Safety and Health (NIOSH) certification standards as do self-contained breathing apparatus. The potential for wide application makes creation of a "standard" suit test impractical. However, standard methods for data sampling and collection may be practical. For example, continuous sampling of the breathing zone at a particular location may eliminate testing irregularities. Also, skin and body temperature sampling according to the extensive work done by Ralph F. Goldman could be referenced.

Finally, it is important that the potential user of a whole body protective suit be knowledgeable about the physiologic impact a suit may present to his workmen. When engineering controls cannot eliminate the hazard, then the use of protective equipment is indicated. This use must be appropriate for the hazard and not compromise other aspects of worker safety or health.